Chapter 2: Heat Integration through Pinch Technology

2.1 Introduction

This chapter lays out the basic principles for analyzing a system of hot and cold streams. Hot streams require cooling to lower their supply temperatures to desired target temperatures, while cold streams need heating to raise their supply temperatures to specified target temperatures. This chapter also compares the minimum heating- and cooling-utility targets for systems without and with heat integration.

We begin by defining the heating/cooling process as a heat-transfer problem in which heat is transferred from a set of hot streams to a set of cold streams (Section 2.2). We discuss the data required for the analysis and suggest methods for data extraction (Section 2.3). Next, we analyze the system without allowing heat integration between hot and cold streams to identify maximum heating- and cooling-utility targets (Section 2.4). Finally, we determine minimum utility requirements for an integrated system that employs maximum heat integration between hold and cold streams (Section 2.5). For these analyses, we introduce *the temperature-enthalpy diagram, the hot and cold composite curves, the temperature-interval diagram,* and *the concept of the pinch temperature*.

2.2 Temperature-Enthalpy Diagram (T-Q Diagram)

Before investigating heat integration for a given manufacturing process, we introduce a graphical tool, called *the temperature-enthalpy diagram (T-Q diagram)*, for depicting the heat transfer between any two hot and cold streams.

Figure 2.1 is a conventional process flow diagram (PFD) of a heat-exchanger unit. In the figure, 1000 kW of heat are transferred from the hot stream to the cold stream. The hot stream and cold stream enter the unit at 100 and 20 °C, respectively, and leave the unit at 50 and 80 °C, respectively.

The T-Q diagram is an alternative technique that gives useful insights into the temperature-driving force for heat transfer between the streams. Figure 2.2 is a plot of temperature (y-axis) versus enthalpy or heat transferred (x-axis) for the same heat-exchanger unit depicted in Figure 2.1. In this case, the hot stream (solid line) enters the heat exchanger from the right side of Figure 2.2 at 100 °C and leaves at the left side at 50 °C. For true counter current heat transfer, the cold stream (dashed line) enters the exchanger from the left side of Figure 2.2 at 20 °C and exits at the right side at 80 °C. The horizontal distance (1,000 kW) corresponds to the heat-transfer rate from the hot stream, Q_H, to the cold stream, Q_C.

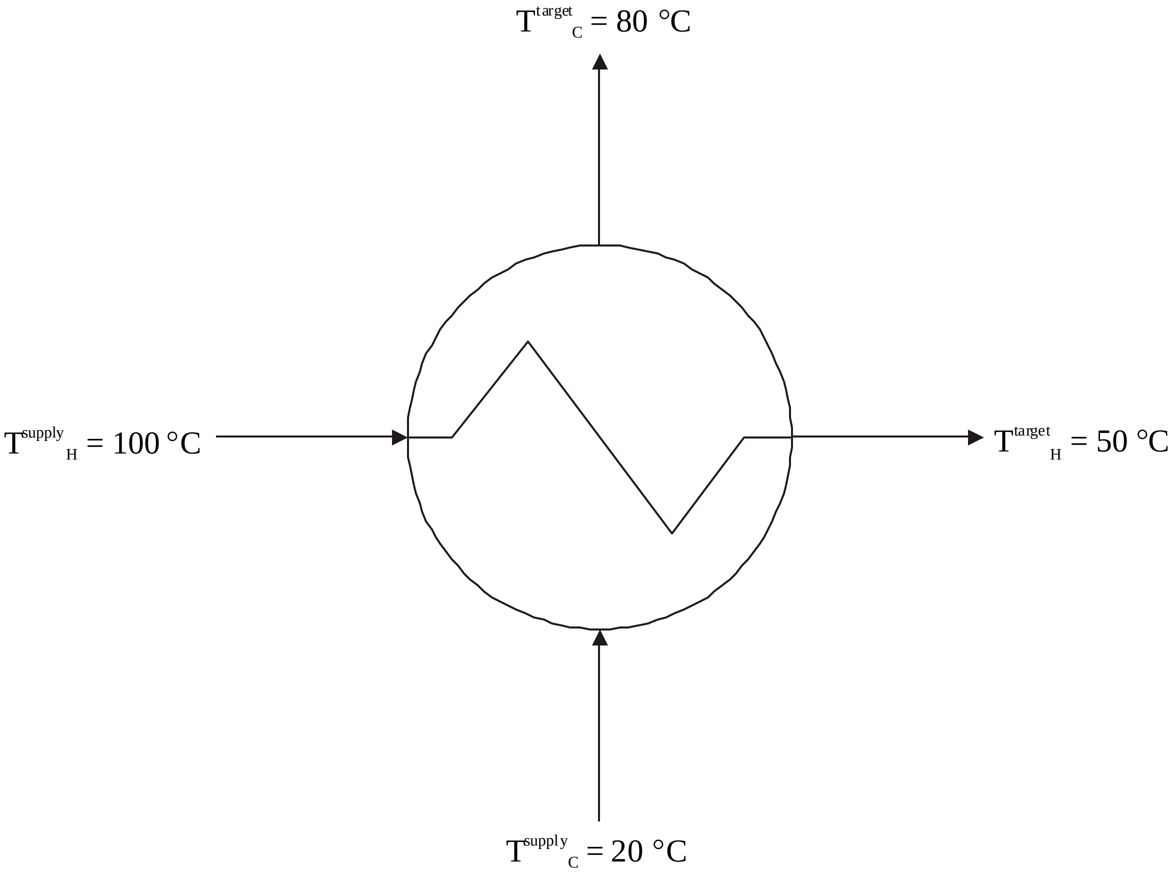

Figure 2.1. Process flow diagram (PFD) of a heat exchanger.

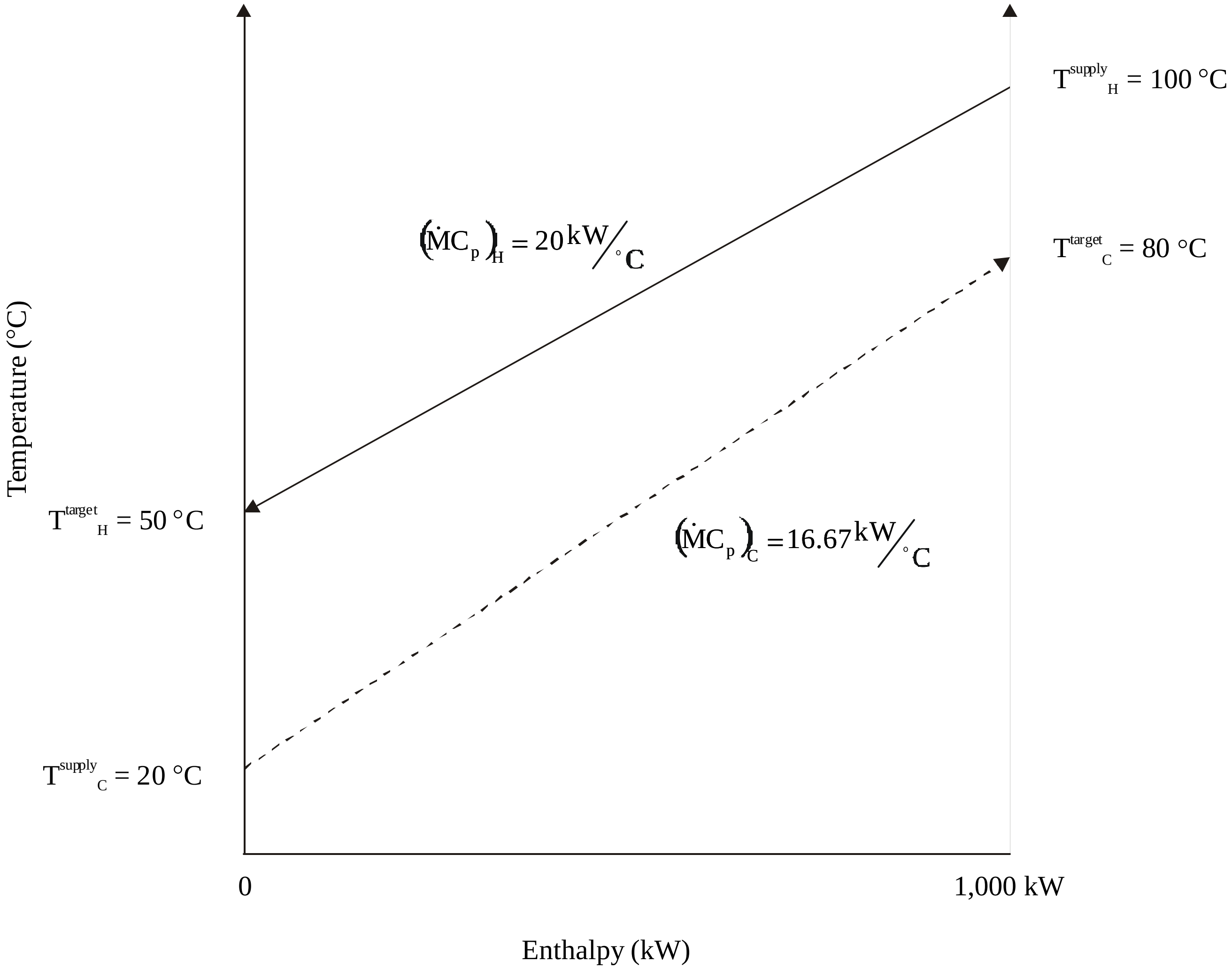

Figure 2.2. Temperature-enthalpy diagram (T-Q diagram) for representing the heat exchanger introduced in Figure 2.1.

The slope of the hot (solid line) or cold (dashed line) stream line is inversely proportional to the ability of the stream to give off or accept heat. The total heat transferred from the hot stream ΔH_H (Equation 2.1) or to the cold stream ΔH_C (Equation 2.2) is:

$$\Delta H_H(\mathrm{kW}) = \left(\dot{M}C_p\right)_H\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)\left[T_H^{\mathrm{supply}} - T_H^{\mathrm{target}}\right]\left(^\circ\mathrm{C}\right) \tag{2.1}$$

$$\Delta H_C(\mathrm{kW}) = \left(\dot{M}C_p\right)_C\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)\left[T_C^{\mathrm{target}} - T_C^{\mathrm{supply}}\right]\left(^\circ\mathrm{C}\right) \tag{2.2}$$

where the capacity flowrate, $\left(\dot{M}C_p\right)_i$, refers to the product of the mass flow rate, $\dot{M}_i$, and the heat capacity, $C_{p,i}$, of each stream i. The slopes of the hot (Equation 2.3) and cold (Equation 2.4) stream lines in Figure 2.2 are:

$$\begin{aligned}\text{slope} &= \left(\dot{M}C_p\right)_H\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) = \frac{\Delta H_H(\mathrm{kW})}{\left[T_H^{\mathrm{supply}} - T_H^{\mathrm{target}}\right]\left(^\circ\mathrm{C}\right)} \\ &= \frac{1000\mathrm{kW}}{[100-50]\left(^\circ\mathrm{C}\right)} = 20\frac{\mathrm{kW}}{^\circ\mathrm{C}}\end{aligned} \tag{2.3}$$

$$\begin{aligned}\text{slope} &= \left(\dot{M}C_p\right)_C\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) = \frac{\Delta H_C(\mathrm{kW})}{\left[T_C^{\mathrm{target}} - T_C^{\mathrm{supply}}\right]\left(^\circ\mathrm{C}\right)} \\ &= \frac{1000\mathrm{kW}}{[80-20]\left(^\circ\mathrm{C}\right)} = 16.67\frac{\mathrm{kW}}{^\circ\mathrm{C}}\end{aligned} \tag{2.4}$$

The vertical spacing between the hot and cold streams is a measure of the temperature-driving force for heat transfer. In this case, we see *a minimum approach temperature* of 20 °C between the hot-stream inlet and the cold-stream outlet in Figures 2.1 and 2.2. We discuss the concept of a minimum approach temperature in detail in Section 2.2.2.

2.3 Data Extraction

2.2.1 Introduction

Table 2.1 lists the stream data for two hot streams and two cold streams of Example 2.1.

Table 2.1. Stream data for Example 2.1.

Stream i	T^{supply}_i (°C)	T^{target}_i (°C)	$\left(\dot{M}C_p\right)_i$ (kW/°C)	DH_i (kW)
H1	165	35	20	2600
H2	115	55	40	2400
C1	50	185	30	4050
C2	70	142	15	1080

2.2.2 Minimum Approach Temperature

In Section 2.2, we briefly described the minimum approach temperature between a hot and cold stream in a heat exchanger. Specifically, for true countercurrent contact between the hot stream and cold stream in Figure 2.2, a minimum approach temperature of 20 °C exists between the supply temperature of the hot stream, and the target temperature of the cold stream.

For simplicity, we often *incorporate a minimum approach temperature into the stream data by subtracting* $\Delta T_{min}/2$ *from the hot-stream supply and target temperatures and adding* $\Delta T_{min}/2$ *to the cold-stream supply and target temperatures*. For Example 2.1, we incorporate a minimum approach temperature, ΔT_{min}, of 20 °C by first subtracting 10 °C ($\Delta T_{min}/2$ = 20 °C/2 = 10 °C) from the supply and target temperatures of streams H1 and H2, and then adding 10 °C to the supply and target temperatures of streams C1 and C2. Table 2.2 lists the resulting stream data for Example 2.1 reflecting a minimum approach temperature of 20 °C. We call this modified set of stream data the "shifted" stream data.

Table 2.2. Shifted stream data for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

Stream i	T^{supply}_i **(°C)**	T^{target}_i **(°C)**	$(\dot{M}C_p)_i$ **(kW/°C)**	ΔH_i **(kW)**
H1	175	45	20	2600
H2	125	65	40	2400
C1	60	195	30	4050
C2	80	152	15	1080

Figure 2.3 illustrates a T-Q diagram where we have included the minimum approach temperature in the stream data. In the figure, the vertical spacing between the hot-stream (solid bold) supply temperature and the cold-stream (dashed bold) target temperature is zero. Since the temperature data represent the "shifted" values, a zero temperature difference does *not* reflect a

zero driving force for heat transfer. In this case, zero vertical spacing between hot and cold streams reflects a temperature-driving force equal to the minimum approach temperature.

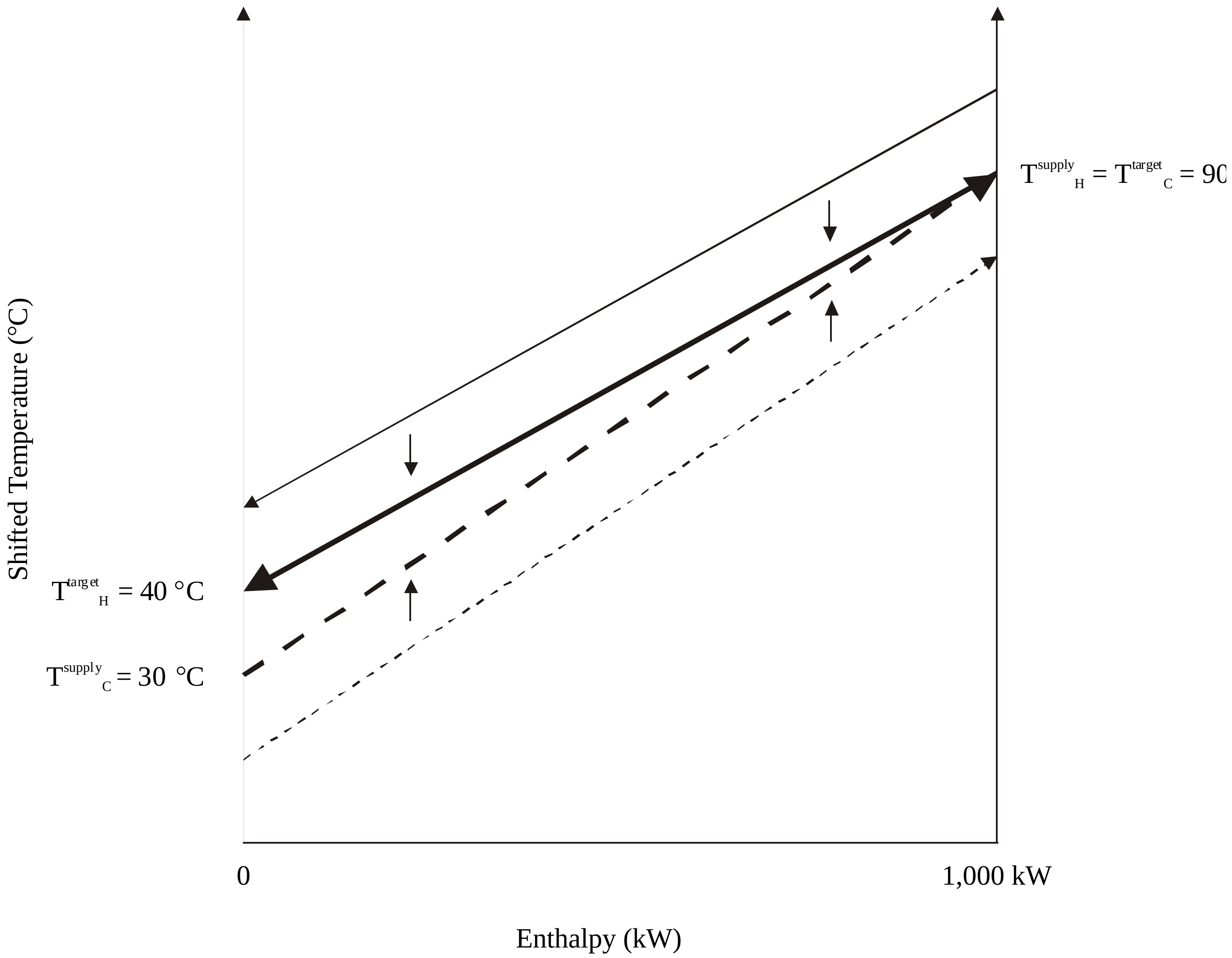

Figure 2.3. Temperature-enthalpy diagram on a shifted temperature scale including a minimum approach temperature of 20 °C in the stream data.

2.4 Minimum Utility Targets without Heat Integration

2.4.1 T-Q Diagrams

The first step to analyze the heating- and cooling-utility duties for the system in Example 2.1 is identifying *the maximum heating- and cooling-utility duties without heat integration*. In this section, we apply the T-Q diagram to identify the heating- and cooling- utility duties and illustrate the placement of a variety of utilities for each stream in Example 2.1.

Figure 2.4 shows a T-Q diagram for each stream in Example 2.1. In the figure, hot streams H1 and H2 exhibit a negative slope, while cold streams C1 and C2 exhibit a positive slope. We can determine the heat-transfer rates from hot streams, or to cold streams, through Equations 2.1 and 2.2. We use the supply and target temperatures defined in the shifted stream data of Table 2.2. The heat calculated will be identical for both the original and shifted temperatures when we assume a constant capacity flowrate.

$$\begin{aligned}
Q_{H1}(\mathrm{kW}) &= (\dot{M}C_p)_{H1}\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)\left[T_{H1}^{\mathrm{supply}} - T_{H1}^{\mathrm{target}}\right](^\circ\mathrm{C}) \\
&= \left(20\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)[155-25](^\circ\mathrm{C}) \\
&= 2600\,\mathrm{kW}
\end{aligned}$$

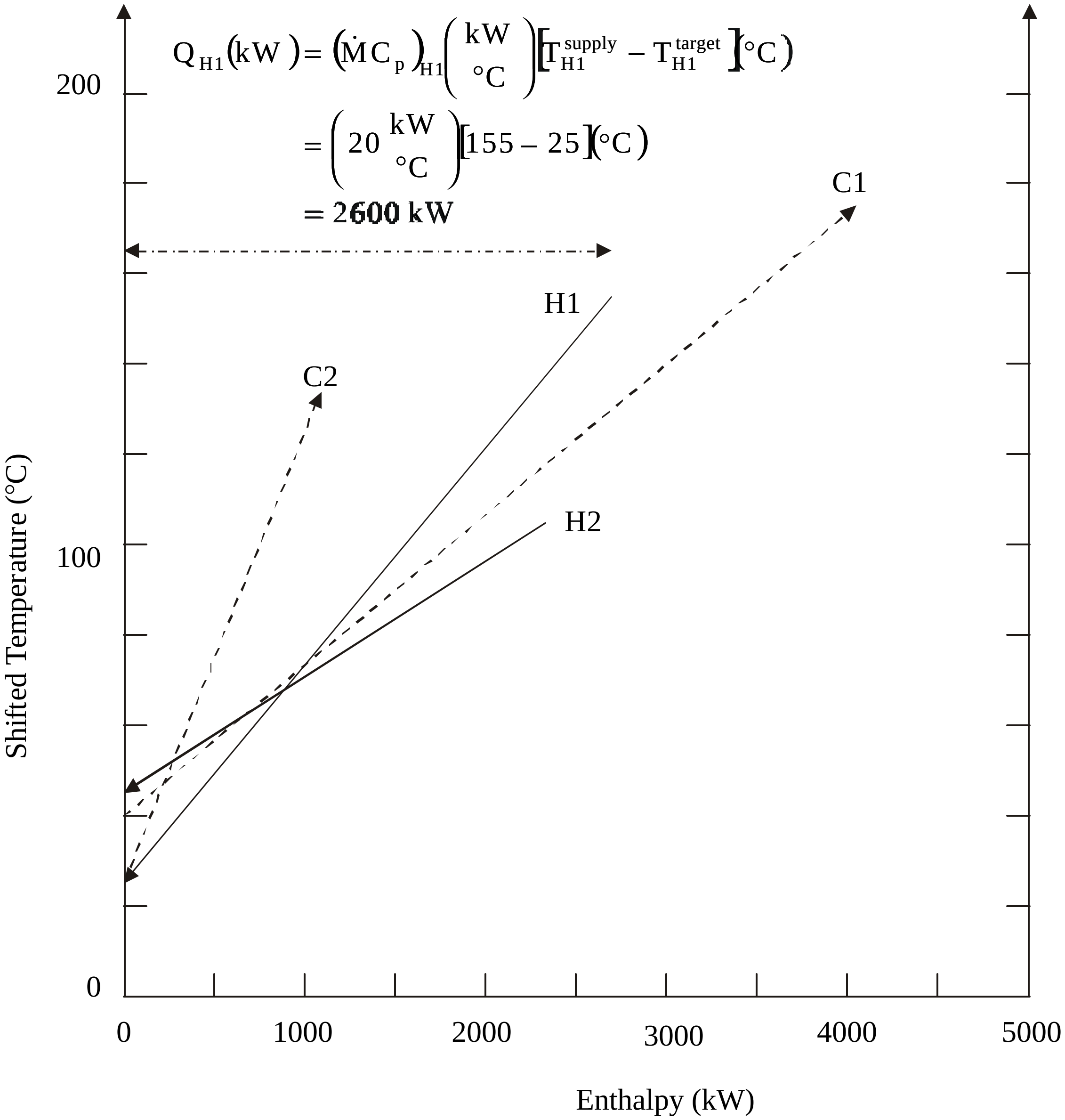

Figure 2.4. T-Q diagram for each stream in Example 2.1.

$$\begin{aligned} Q_{H2}(\mathrm{kW}) &= \left(\dot{M}C_p\right)_{H2}\left(\frac{\mathrm{kW}}{°\mathrm{C}}\right)\left[T_{H2}^{\mathrm{supply}} - T_{H2}^{\mathrm{target}}\right](°\mathrm{C}) \\ &= \left(40\,\frac{\mathrm{kW}}{°\mathrm{C}}\right)[105 - 45](°\mathrm{C}) \\ &= 2400\,\mathrm{kW} \end{aligned}$$

$$\begin{aligned} Q_{C1}(\mathrm{kW}) &= \left(\dot{M}C_p\right)_{C1}\left(\frac{\mathrm{kW}}{°\mathrm{C}}\right)\left[T_{C1}^{\mathrm{target}} - T_{C1}^{\mathrm{supply}}\right](°\mathrm{C}) \\ &= \left(30\,\frac{\mathrm{kW}}{°\mathrm{C}}\right)[175 - 40](°\mathrm{C}) \\ &= 4050\,\mathrm{kW} \end{aligned}$$

$$\begin{aligned} Q_{C2}(\mathrm{kW}) &= \left(\dot{M}C_p\right)_{C2}\left(\frac{\mathrm{kW}}{°\mathrm{C}}\right)\left[T_{C2}^{\mathrm{target}} - T_{C2}^{\mathrm{supply}}\right](°\mathrm{C}) \\ &= \left(15\,\frac{\mathrm{kW}}{°\mathrm{C}}\right)[132 - 60](°\mathrm{C}) \\ &= 1080\,\mathrm{kW} \end{aligned}$$

The total heats transferred from hot streams, Q^{tot}_H, and to cold streams, Q^{tot}_C, are simply the sums $Q_{H1} + Q_{H2}$ and $Q_{C1} + Q_{C2}$, respectively. Q^{tot}_H and Q^{tot}_C reflect the total heating- and cooling-utility duties, respectively, for Example 2.1 without heat integration.

$$Q_H^{tot} = Q_{H1} + Q_{H2} = 2600\,\mathrm{kW} + 2400\,\mathrm{kW} = 5000\,\mathrm{kW}$$

$$Q_C^{tot} = Q_{C1} + Q_{C2} = 4050\,\mathrm{kW} + 1080\,\mathrm{kW} = 5130\,\mathrm{kW}$$

According to Table 2.3, then, the maximum total heating- and cooling-utility duties required for Example 2.1 are 4305 and 3700 kW, respectively.

Table 2.3. Maximum heating- and cooling-utility duties (i.e., without heat integration) in Example 2.1.

Stream i	Maximum Heating Utility Duty (kW)	Maximum Cooling Utility Duty (kW)
H1	0	2600
H2	0	2400
C1	4050	0
C2	1080	0
Total	5130	5000

2.4.2 Heating-Utility Placement for Cold Streams

Figure 2.5 is a T-Q diagram representing the heating of cold steam 1 (solid sloped line) of Example 2.1 with three alternatives heating utilities, assuming a minimum approach temperature, ΔT_{min}, of 20 °C. In the figure, we use high-pressure steam (solid horizontal line), low-pressure steam (dashed horizontal line) and hot oil (dashed sloped line) to supply 1300 kW of heat. Both horizontal lines (high- and low-pressure steam) represent constant-temperature heating utilities due to the condensing nature of steam utilities. Section 4.3.2 discusses the proper selection of steam qualities for heating utilities (i.e., high-pressure versus low-pressure steam). On the other hand, hot flue gas from a fired furnace is drawn as a sloped line to represent cooling of the gas in the unit. Note that the flowrate of the flue gas is inversely proportional to the slope of the line representing the fired furnace. Section 6.2 examines the optimal design of fired heaters.

Table 2.4. Typical heating utilities and operating temperatures.

Heating Utility	**Supply Temperature °C**	**Target Temperature °C**
Low-Pressure Steam	190	-
High-Pressure Steam	240	-
Flue Gas	1500	265

It is important to adjust the temperatures of heating utilities for a minimum approach temperature by subtracting $\Delta T_{min}/2$ *from the supply temperatures of steams as well as the supply and target temperatures for the hot-oil circuit.*

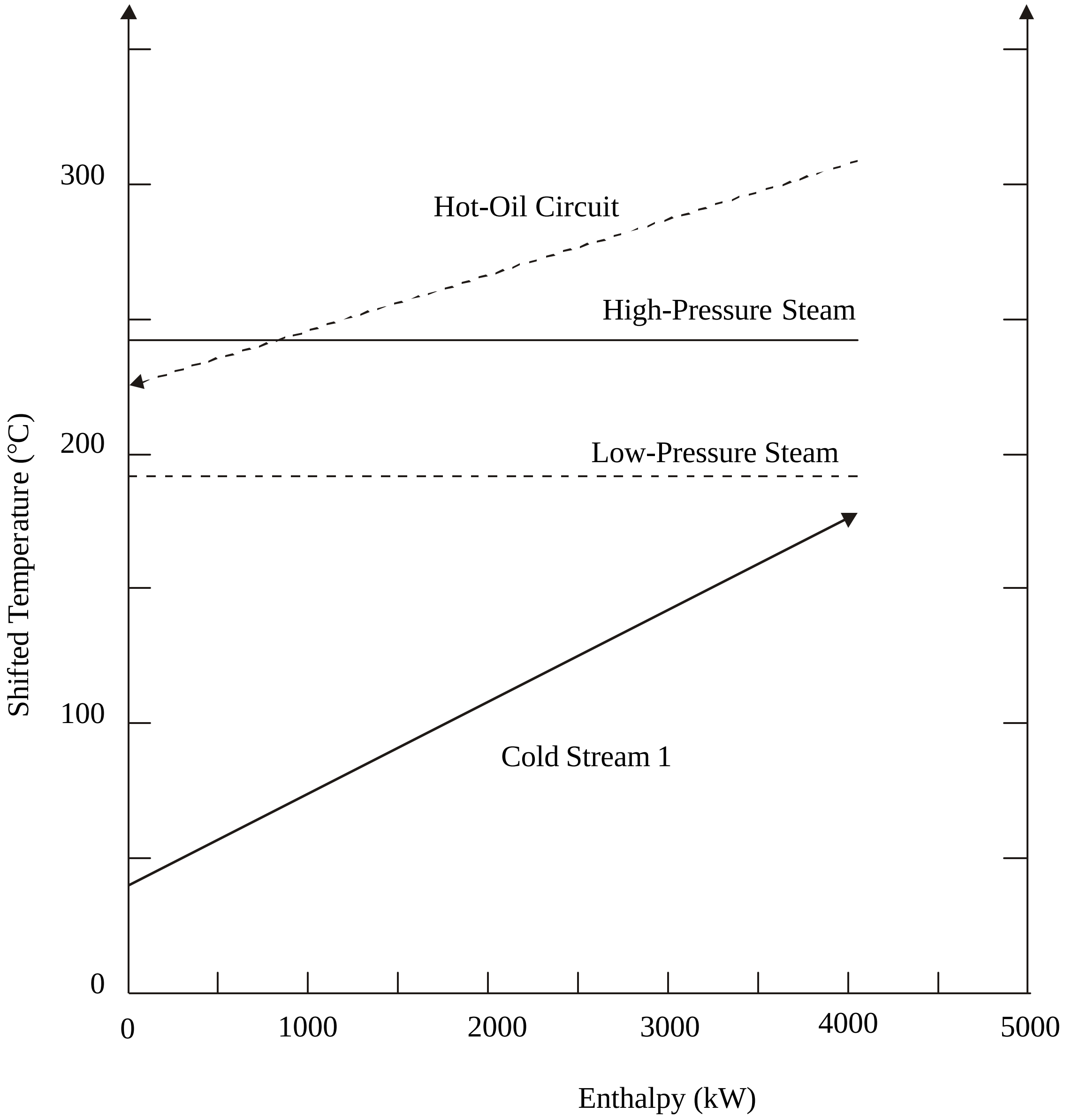

Figure 2.5. T-Q diagram representing the heating of cold stream 1 of Example 2.1 with low-pressure steam, high-pressure steam and hot oil.

2.4.3 Cooling-Utility Placement for Hot Streams

Figure 2.6 is a T-Q diagram representing the cooling of hot steam 2 (solid line) of Example 2.1 with cooling water (dashed line). In the figure, cooling water is represented by a sloped line (i.e., variable-temperature utility). A typical range for the supply and target temperatures of cooling water is 25 to 45 °C. We have drawn the cooling water from 35 to 55 °C to reflect the minimum approach temperature of 20 °C. *Once again, we must adjust the supply and target temperatures of cooling utilities by adding ΔTmin/2 to account for a minimum approach temperature for heat transfer.*

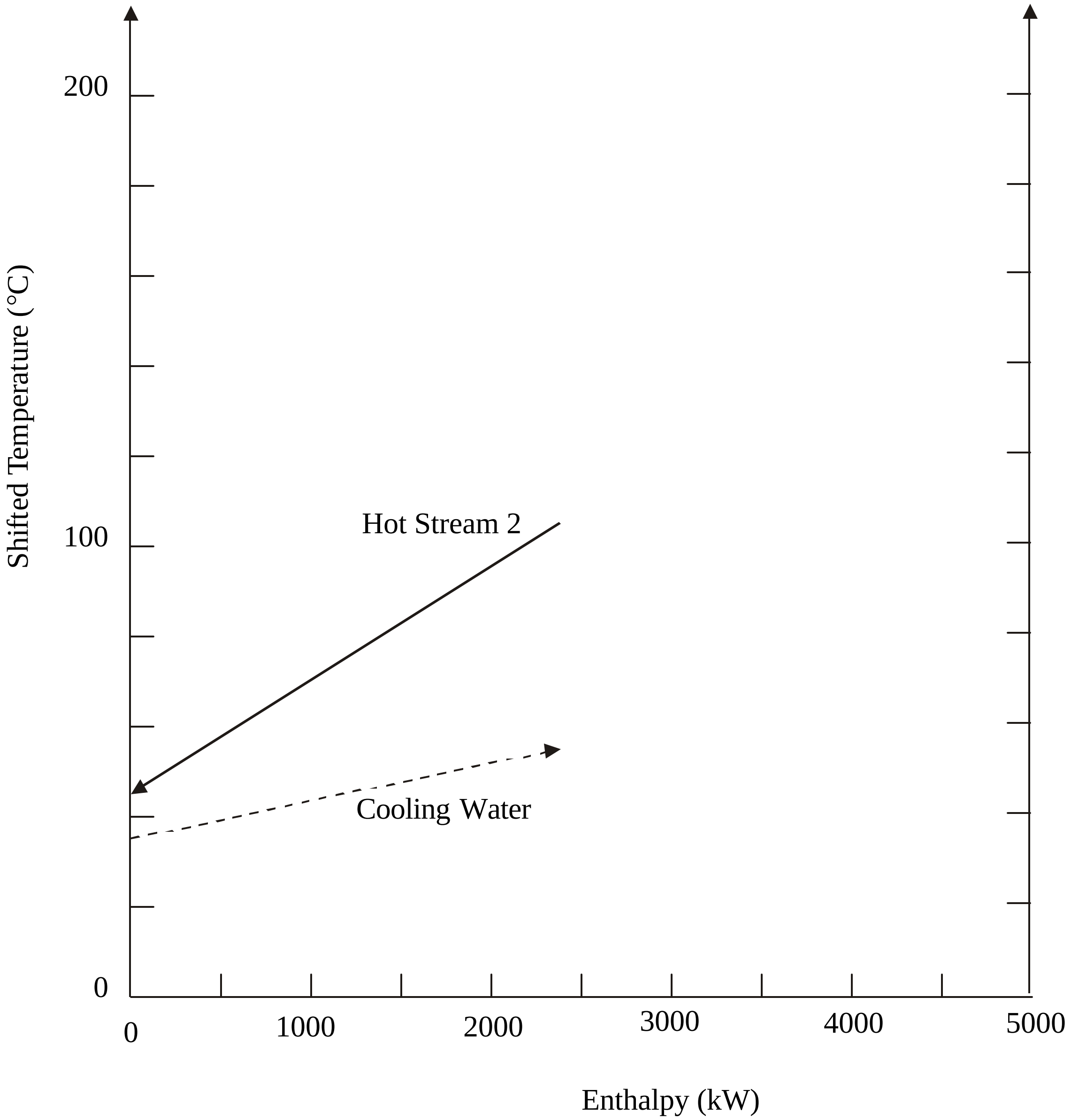

Figure 2.6. T-Q diagram representing the cooling of hot stream 2 of Example 2.1 with cooling water.

2.5 Minimum Utility Targets with Heat Integration

We turn to process integration and demonstrate how to reduce heating- and cooling-utility consumptions to their minimum values simply by taking into account all the hot and cold streams simultaneously and favoring heat recovery between hot and cold streams, rather than simply heating and cooling with utility streams. Example 2.1 (Table 2.2) illustrates the construction of composite curves that represent the heating and cooling demands of the entire system and identify minimum utility requirements. We discuss the composite curves below.

2.5.1 Hot and Cold Composite Curves

The essential step in this type of process integration is representing the individual hot and cold streams on a *single* diagram and determining the minimum utility duties for the entire system. Such a diagram may either be a graphical representation, called *a composite curve,* or a table, called *a temperature-interval diagram (TID).*

2.5.1.1 Graphical Approach: Hot and Cold Composite Curves

First, let us consider the graphical method, called the hot and cold composite curves. Constructing a composite curve graphically is a four-step procedure:

1. First, plot all of the shifted hot streams involved on a single T-Q diagram. The streams should be plotted "head to toe" so that while the y-axis, which corresponds to temperature, is absolute, the x-axis, which corresponds to the enthalpy, is relative, and one hot stream begins where the previous ends. Figure 2.7 displays such a plot for Example 2.1.

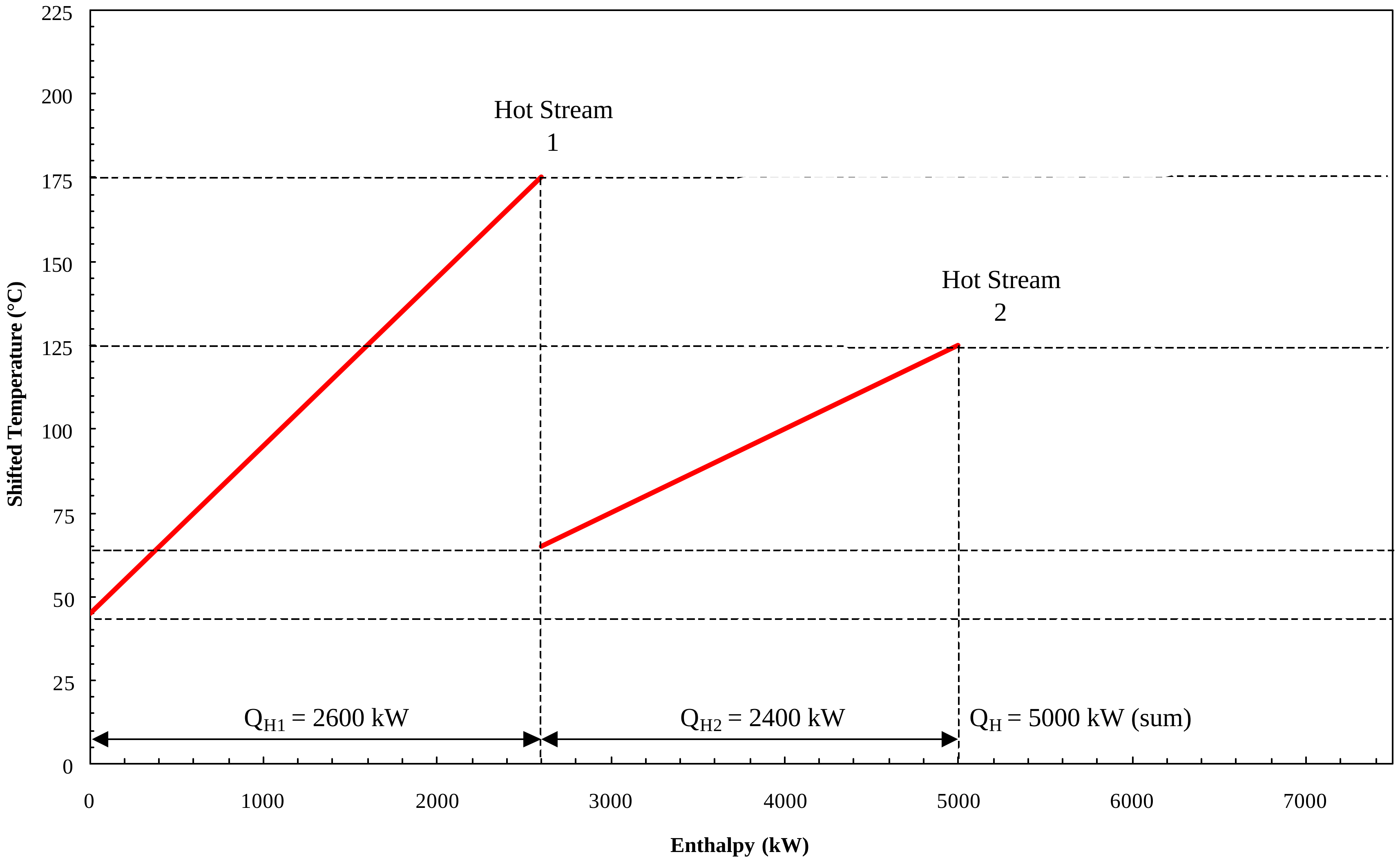

Figure 2.7. Graphical approach to the construction of the hot composite curve for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

2. Divide the y-axis into temperature intervals by drawing horizontal lines (shown as dashed lines on Figure 2.7) at the shifted supply and target temperatures for each hot stream (Table 2.2). Those horizontal lines mark the interval boundaries, denoted as T^*_k (where k = 1, 2, 3, …). In Example 2.1, these intervals occur at 25, 45, 105 and 155 °C.

3. Sum the heat loads of all hot streams present in each temperature interval and draw a new line across the interval corresponding to that sum. For example, the first temperature interval (from $T^*_1 = 25$ to $T^*_2 = 45$ °C) includes only 400 kW of heat from hot stream 1 and the new line falls exactly on the line for hot stream 1. However, the second temperature interval (from $T^*_2 = 45$ to $T^*_3 = 105$ °C) contains both 1200 kW of heat from hot stream 1 and 2400 kW from hot stream 2. Figure 2.8 shows the result of this procedure for the hot composite curve of Example 2.1.

4. Construct the final hot composite curve by eliminating the original stream lines from the diagram and leaving only the sum of the heat loads within each temperature interval. Figure 2.9 shows the final hot composite curve for Example 2.1.

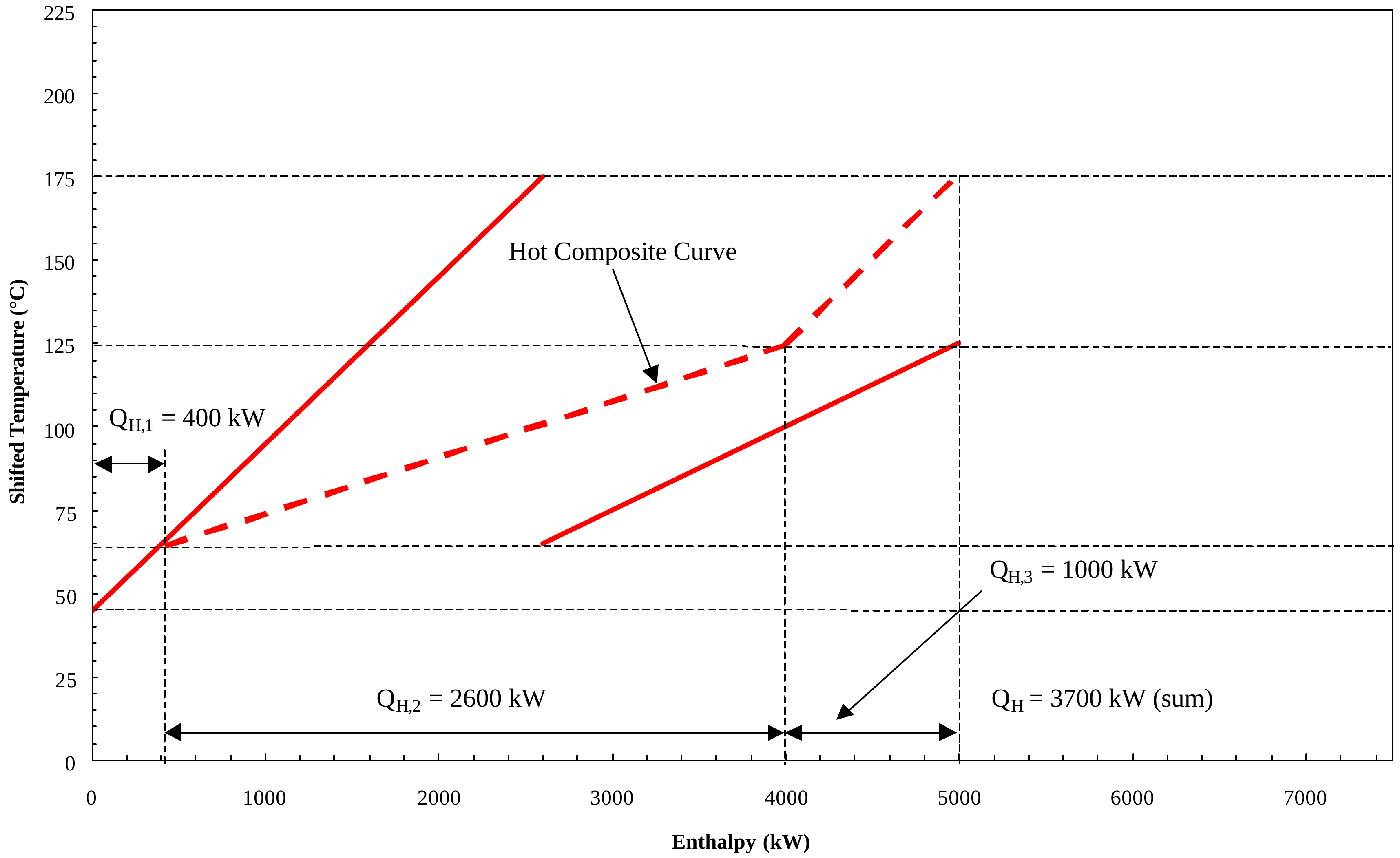

Figure 2.8. Cumulative hot stream (dashed lines) for each interval constructed in Figure 2.7 for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

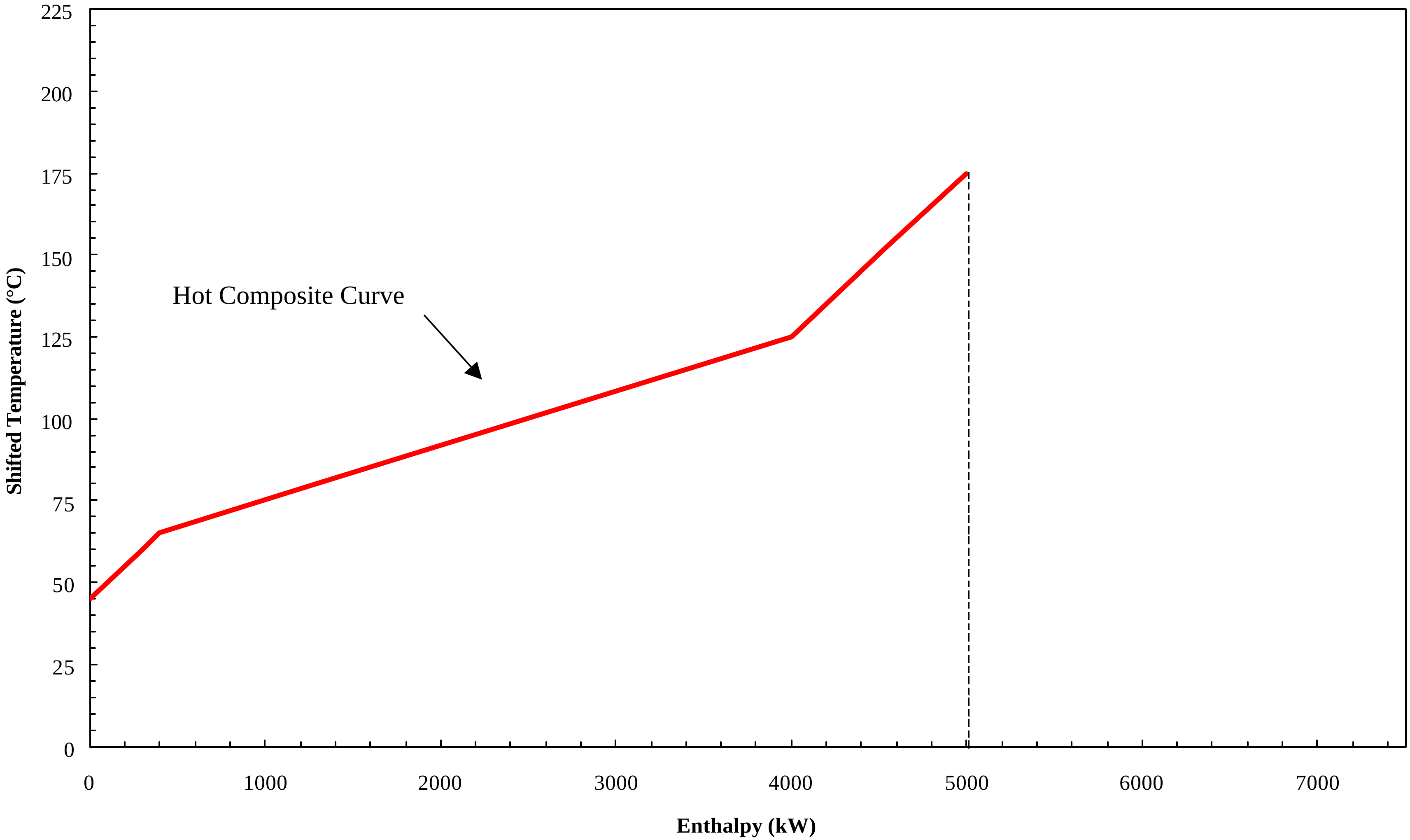

Figure 2.9. Hot composite curve for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

5. Repeat steps 1 through 4 for cold streams. In this case, the temperature-interval boundaries T^*_k are 30, 50, 122 and 165 °C. Figures 2.10 to 2.12 illustrate the construction of the cold composite curve for Example 2.1.

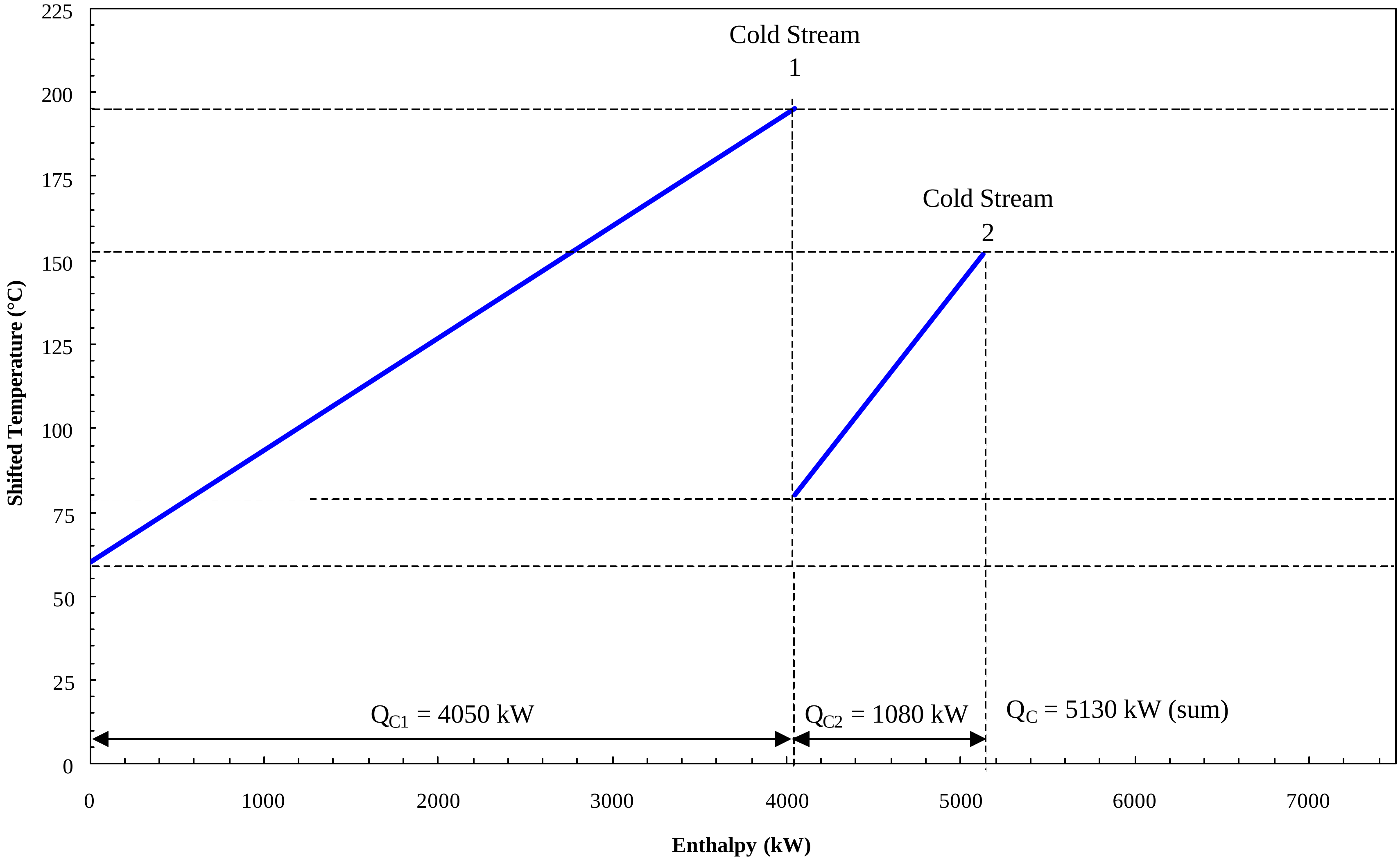

Figure 2.10. Graphical approach to the construction of the cold composite curve for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

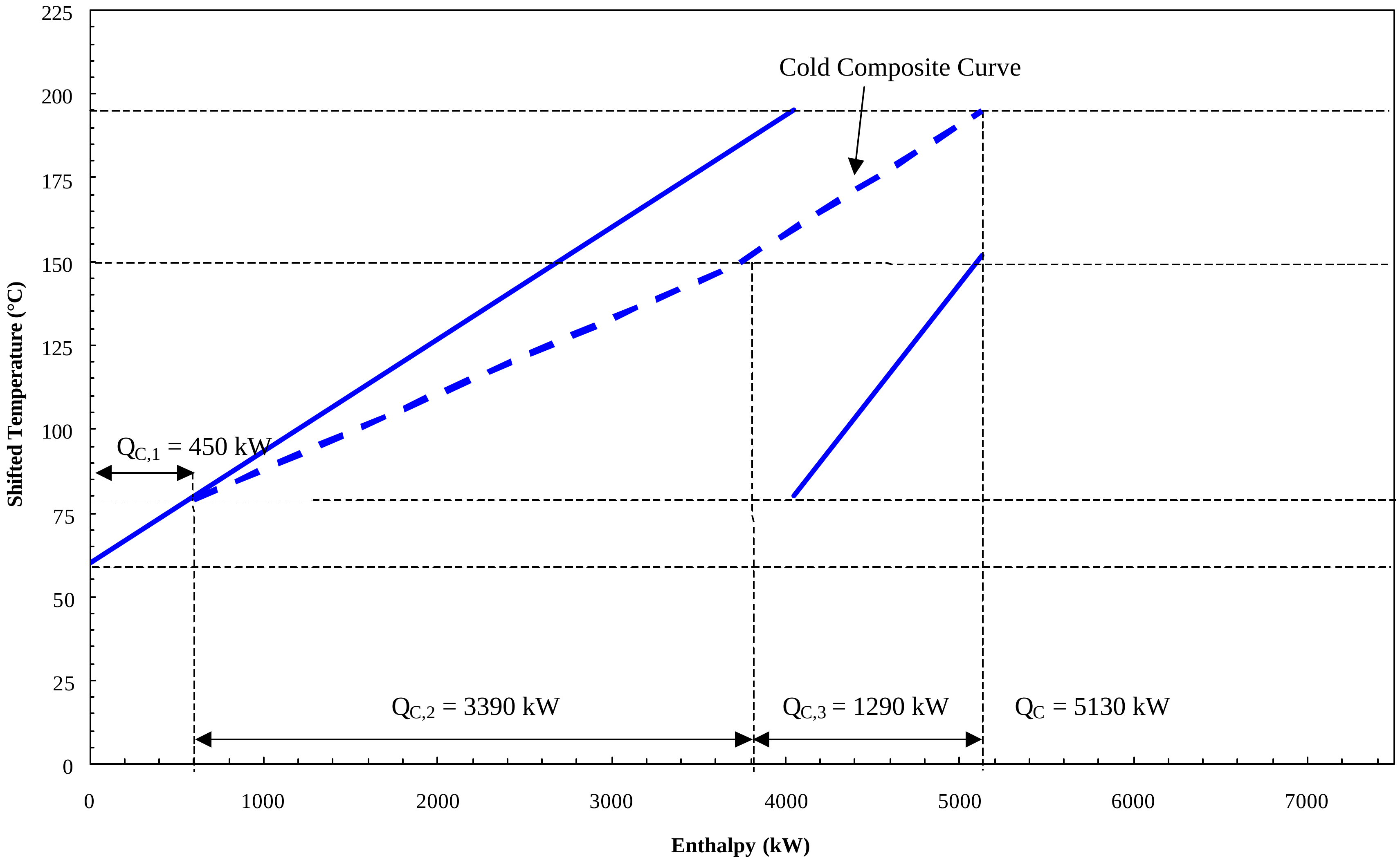

Figure 2.11. Cumulative cold stream (dashed lines) for each interval constructed in Figure 2.10 for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

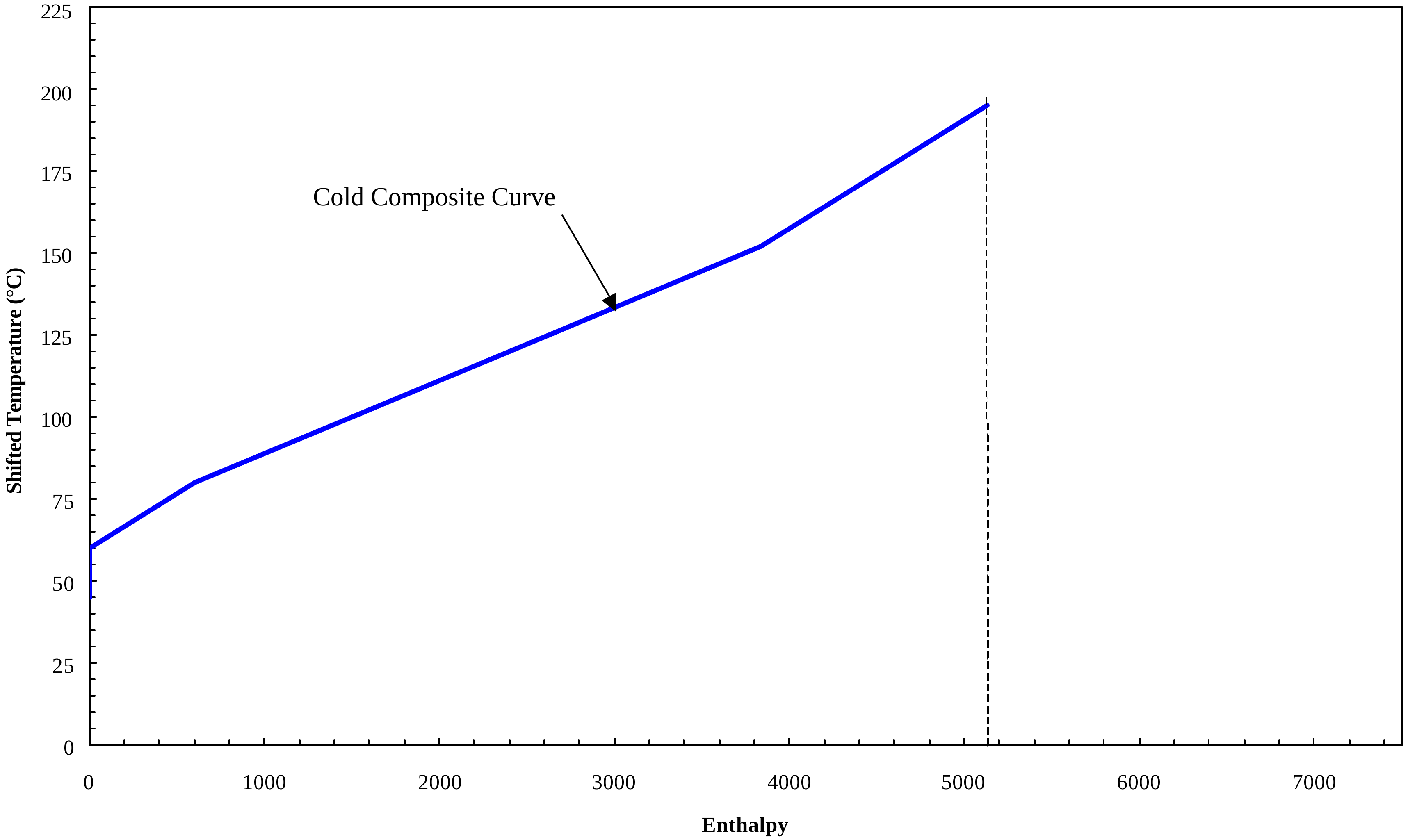

Figure 2.12. Cold composite curve for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

2.5.1.2 Tabular Approach: Temperature-Interval Diagram (TID)

Since graphical construction is often fairly involved, we can solve most problems more effectively by using a tabular method, that is more readily adaptable to computer programming. The TID provides all the necessary information to create a heat-exchanger network, but avoids the construction of composite curves. However, it is true that the graphical method provides useful insights to heat integration that are not available in the tabular form.

As in the graphical method, the tabular method uses the temperature-interval boundaries determined from the shifted supply and target temperatures of both hot and cold streams (such as Table 2.2). In this case, we sort the shifted supply and target temperatures in ascending order to form the temperature-interval boundaries, T^*_k (where k = 1, 2, 3, …, n_{int}). Here, n_{int} is the number of temperature-interval boundaries. Once we have defined the temperature intervals, we can proceed as follows.

1. For a given temperature interval, k, calculate the heat surplus from each hot stream i, in the interval, $Q_{Hi,k}$. For each temperature interval, k, Equation 2.1 becomes:

$$Q_{Hi,k}(\text{kW}) = \left(\dot{M}C_p\right)_{Hi}\left(\frac{\text{kW}}{{}^\circ\text{C}}\right)\left[T^*_{k+1} - T^*_k\right]({}^\circ\text{C}) \qquad (2.5)$$

where $\left(\dot{M}C_p\right)_{Hi}$ is the capacity flowrate of hot stream i, and T^*_{k+1} and T^*_k are the upper and lower temperature-interval boundaries of interval k. We can then calculate the total heat surplus, $Q_{H,k}$, in interval k, as the sum of the heat surplus for each hot stream i, in the interval, $Q_{Hi,k}$:

$$Q_{H,k}(\mathrm{kW}) = \left[T^*_{k+1} - T^*_k\right](^\circ\mathrm{C}) \sum_i \left(\dot{M}C_p\right)_{Hi} \left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) \tag{2.6}$$

2. With the intervals in ascending order, calculate the cumulative heat surplus at the end of each temperature-interval boundary by summing the heat loads, $\Delta Q_{H,k}$, to that point:

$$\Delta Q_{H,k} = \sum_k Q_{H,k} \tag{2.7}$$

We return to Example 2.1 and identify the temperature intervals for the overall system from Table 2.2: $T^*_1 = 25$, $T^*_2 = 40$, $T^*_3 = 45$, $T^*_4 = 60$, $T^*_5 = 105$, $T^*_6 = 132$, $T^*_7 = 155$ °C and $T^*_8 = 175$ °C. Table 2.2 also lists the capacity flowrate, $\left(\dot{M}C_p\right)_i$, for each stream.

The first and second intervals, 25 to 40 °C and 40 to 45 °C, have only one hot stream, so the calculations (Equation 2.6) are simply:

$$\begin{aligned} Q_{H,1}(\mathrm{kW}) &= \left[T^*_2 - T^*_1\right](^\circ\mathrm{C})\left[MC_p\right]_{H1}\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) \\ &= [40 - 25](^\circ\mathrm{C})\left(20\,\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) \\ &= 300\,\mathrm{kW} \end{aligned}$$

$$Q_{H,2}\left(\mathrm{kW}\right)=\left[T_3^* - T_2^*\right]\left(^\circ\mathrm{C}\right)\left[MC_p\right]_{H1}\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=\left[45-40\right]\left(^\circ\mathrm{C}\right)\left(20\,\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=100\,\mathrm{kW}$$

The third and fourth intervals, 45 to 60 °C and 60 to 105 °C, contain both hot streams, so the calculations for those intervals:

$$Q_{H,3}\left(\mathrm{kW}\right)=\left[T_4^* - T_3^*\right]\left(^\circ\mathrm{C}\right)\left[\left(MC_p\right)_{H1}+\left(MC_p\right)_{H2}\right]\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=\left[60-45\right]\left(^\circ\mathrm{C}\right)\left[20+40\right]\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=900\,\mathrm{kW}$$

$$Q_{H,4}\left(\mathrm{kW}\right)=\left[T_5^* - T_4^*\right]\left(^\circ\mathrm{C}\right)\left[\left(MC_p\right)_{H1}+\left(MC_p\right)_{H2}\right]\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=\left[105-60\right]\left(^\circ\mathrm{C}\right)\left[20+40\right]\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=2700\,\mathrm{kW}$$

Similarly, the fifth and sixth intervals contain only hot stream 1. The calculations are:

$$Q_{H,5}\left(\mathrm{kW}\right)=\left[T_6^* - T_5^*\right]\left(^\circ\mathrm{C}\right)\left[MC_p\right]_{H1}\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=\left[132-105\right]\left(^\circ\mathrm{C}\right)\left(20\,\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right)$$

$$=540\,\mathrm{kW}$$

$$\begin{aligned} Q_{H,6}\,(\mathrm{kW}) &= \left[T_7^* - T_6^*\right](^\circ\mathrm{C})\left[MC_p\right]_{H1}\left(\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) \\ &= \left[155 - 132\right](^\circ\mathrm{C})\left(20\,\frac{\mathrm{kW}}{^\circ\mathrm{C}}\right) \\ &= 460\ \mathrm{kW} \end{aligned}$$

No hot stream is present in the 7th temperature interval (i.e., $Q_{H,7} = 0$).

Table 2.7 lists the heat surplus over each interval, as well as the cumulative heat surplus at the end of each interval. The cumulative heat surplus for temperature-interval boundaries 0 and 1 are simply $\Delta Q_{H,0} = 0$ and $\Delta Q_{H,1} = \Delta Q_{H,0} + Q_{H,1} = 300$ kW, respectively. The cumulative heat surplus for interval boundary 2 is $\Delta Q_{H,1} + Q_{H,2}$ and the cumulative heat surplus for interval 3 is $\Delta Q_{H,2} + Q_{H,3}$, and so on.

Table 2.5. Data required for the construction of the hot composite curve for Example 2.1.

Interval	Shifted Temperature Boundary (°C)	Heat Surplus (kg/hr)	Cumulative Heat Surplus (kg/hr)
1	25 - 40	300	300
2	40 - 45	100	400
3	45 - 60	900	1300
4	60 - 105	2700	4000
5	105 - 132	540	4540
6	132 - 155	460	5000
7	155 - 175	0	5000

3. The hot-stream portion of the TID is now simply a tabular representation of these data. For a system with i hot streams, column 1 contains the temperature-interval boundaries, in ascending order; columns 2 through i + 1 represent each of the i hot streams in the system with respect to their shifted supply and target temperatures; column i + 2 contains the heat surplus from hot streams within each interval; and column i + 3 (the last column) represents the cumulative heat surplus of hot streams.

Table 2.6 is the hot-stream portion of the TID for Example 2.1. A plot of column 1 (temperature) versus column 5 (cumulative heat surplus) gives the hot composite curve of Figure 2.9.

Table 2.6. Hot-stream portion of the temperature-interval diagram (TID) for Example 2.1.

	Hot Streams			
Shifted Temperature (°C)	**H1 10 kW/°C**	**H2 40 kW/°C**	**Heat Surplus (kW)**	**Cumulative Surplus (kW)**
25	▲			0
	│		300	
40	│			300
	│		100	
45	│	▲		400
	│	│	900	
60	│	│		1300
	│	│	2700	
105	│	│		4000
	│		540	
132	│			4540
	│		460	
155	│			5000
			0	
175				5000

4. The data for the cold composite curve are generated in the identical manner.

Table 2.7 is the partial TID for Example 2.1 including the data for the construction of both hot (column 5 versus column 1) and cold (column 9 versus column 1) composite curves.

Table 2.7. Partial TID for Example 2.1 with data to generate both hot and cold composite curves.

Shifted Temperature (°C)	H1 20 kW/°C	H2 40 kW/°C	Heat Surplus (kW)	Cumulative Surplus (kW)	C1 30 kW/°C	C2 15 kW/°C	Heat Deficit (kW)	Cumulative Deficit (kW)
25	▲			0				0
	│		300				0	
40	│			300	│			0
	│		100		│		150	
45	│	▲		400	│			150
	│	│	900		│		450	
60	│	│		1300	│	│		600
	│	│	2700		│	│	2025	
105	│	│		4000	│	│		2625
	│		540		│	│	1215	
132	│			4540	│	▼		3840
	│		460		│		690	
155	│			5000	│			4530
			0		│		600	
175				5000	▼			5130

Figure 2.13 displays the hot and cold composite curves for Example 2.1 on the same plot. Vertical overlap represents possible heat integration. This figure also shows where to apply heating and cooling utilities. We discuss utilities in the following section.

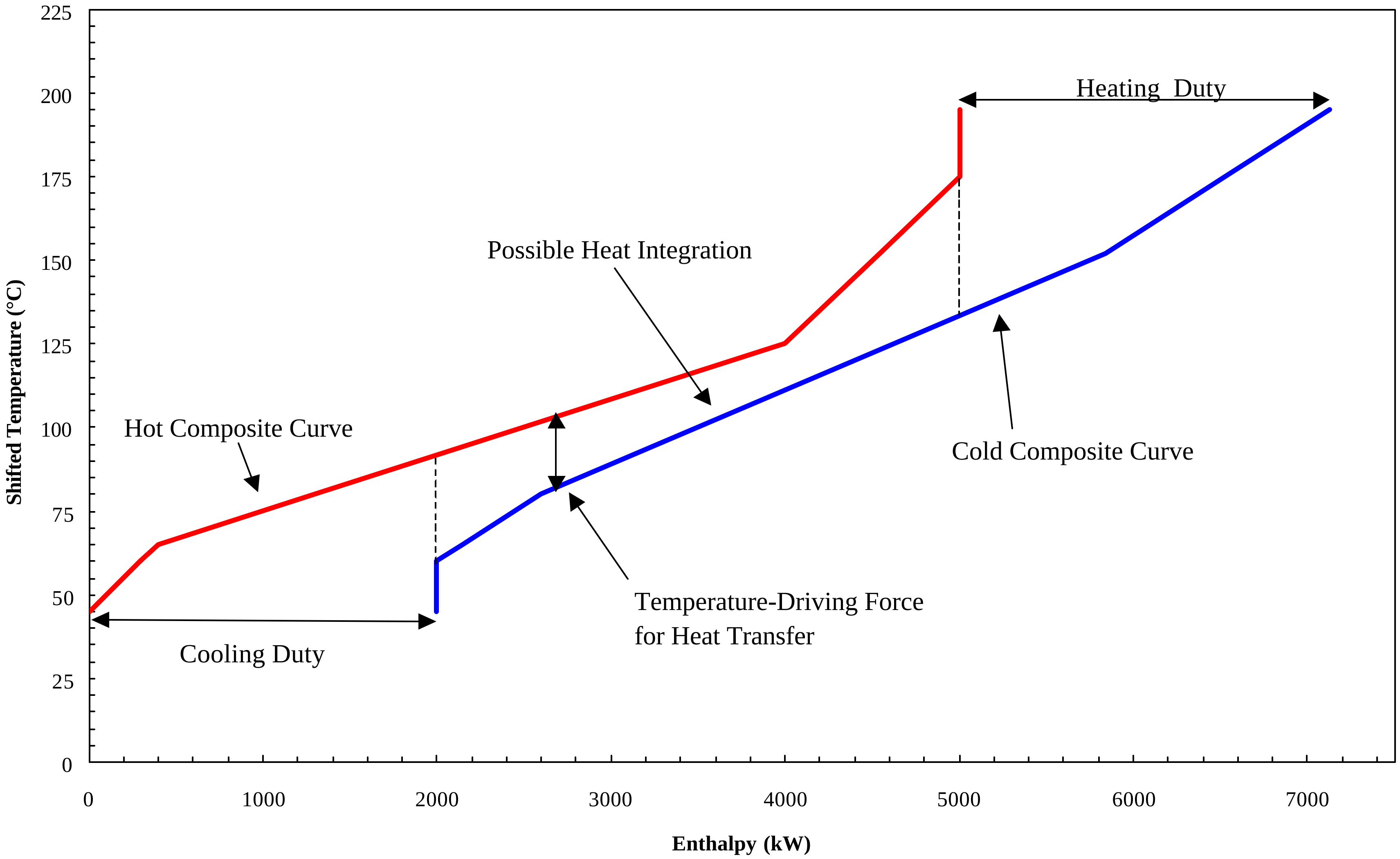

Figure 2.13. Hot and cold composite curves for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

2.5.2 Condensing and Vaporizing Streams

To this point, we have only considered hot and cold streams featuring sensible cooling and heating, respectively. This section describes how to include condensing hot streams and vaporizing cold streams.

Table 2.8 lists the shifted stream data for Example 2.2. Here, we have modified Example 2.1 to include both a vaporizing and a condensing stream. Hot stream H3 represents a stream condensing (Q_{H3} = 1000 kW) at a shifted temperature of 95 °C while cold stream C3 indicates a stream vaporizing (Q_{C3} = 750 kW) at a shifted temperature of 110 °C. To facilitate condensation and vaporization on the temperature-interval diagram (TID), we subtract 1 °C from the shifted target temperature of condensing streams and add 1 °C to the shifted target temperature of vaporizing streams . We treat vaporizing and condensing streams as cold and hot streams, respectively, with a 1 °C temperature change and a capacity flowrate for cold (Equation 2.8) and hot (Equation 2.9) streams of:

$$\left(\dot{M}C_p\right)_{Ci}\left(\frac{kW}{^\circ C}\right) = \frac{Q_{Ci}(kW)}{1\ ^\circ C} \tag{2.8}$$

$$\left(\dot{M}C_p\right)_{Hi}\left(\frac{kW}{^\circ C}\right) = \frac{Q_{Hi}(kW)}{1\ ^\circ C} \tag{2.9}$$

where Q_{Ci} and Q_{Hi} are the vaporization and condensation duties for cold stream i and hot stream i, respectively.

Table 2.8. Shifted stream data for Example 2.2 with evaporating and condensing streams.

Stream i	T^{supply}_i (°C)	T^{target}_i (°C)	$\left(\dot{M}C_p\right)_i$ (kW/°C)	DH_I (kW)
H1	155	25	20	2,600
H2	105	45	40	2,400
H3	95	94	1,000	1,000
C1	175	40	30	4,050
C2	132	60	15	1,080
C3	110	111	750	750

2.5.2.1 Graphical Approach: Hot and Cold Composite Curves

It is straightforward to incorporate vaporizing and condensing streams in cold and hot composite curves, respectively. We represent both vaporizing and condensing streams with horizontal lines.

Figure 2.14 illustrates the construction of the hot composite curve for Example 2.2. In the figure, dashed lines represent individual process streams. Here, the dashed horizontal line represents the condensing process H3. The hot composite curve (solid line) also reflects this horizontal line.

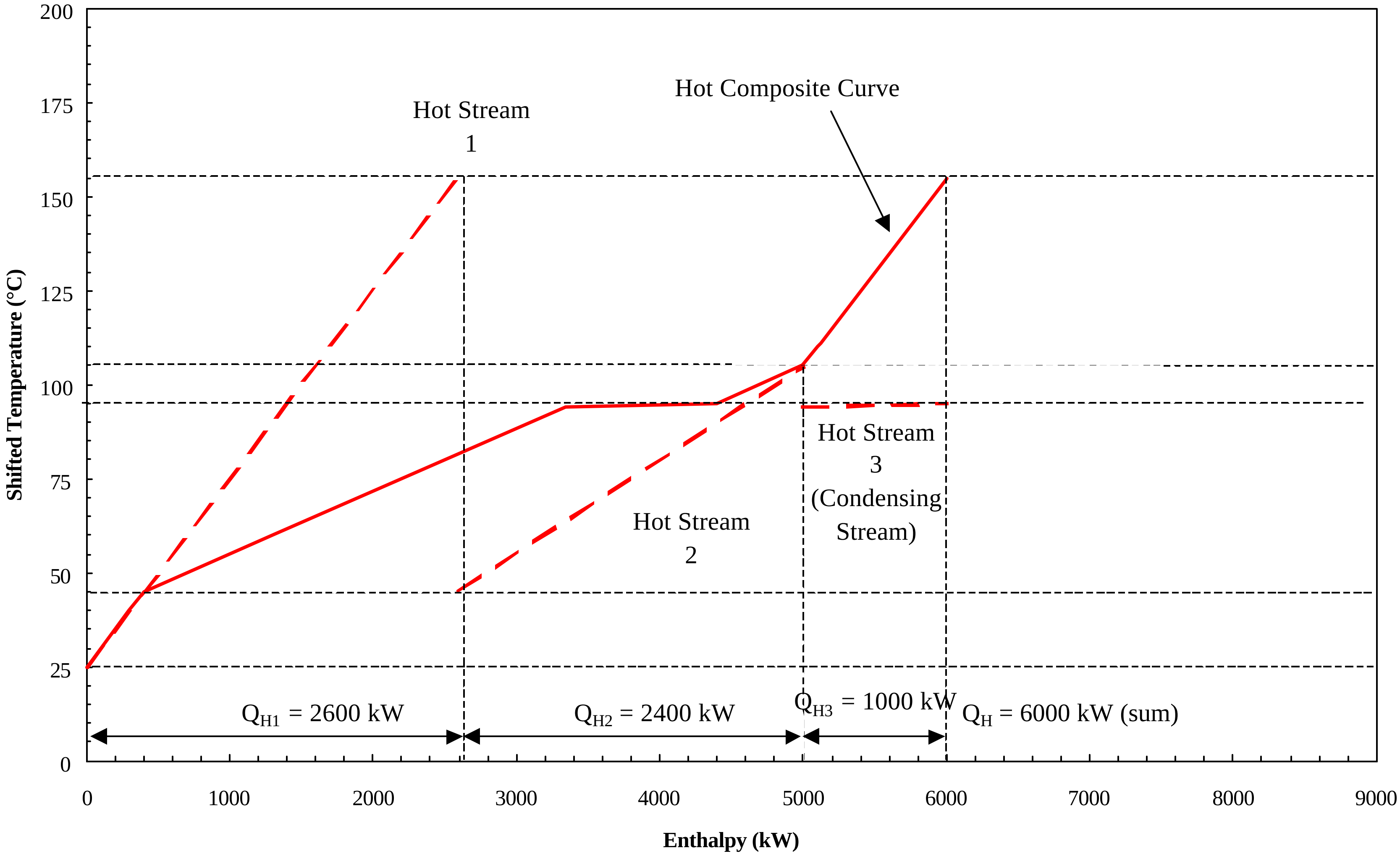

Figure 2.14. Graphical approach to constructing a hot stream composite curve for Example 2.2 with a condensing stream. Temperatures shifted for a minimum approach temperature.

We construct the cold composite curve in the same manner. Figure 2.15 illustrates both the hot and cold composite curves for Example 2.2.

2.5.2.2 Tabular Approach: Temperature-Interval Diagram (TID)

In Table 2.8, we represented both vaporizing and condensing as streams with a temperature of 1 C and a capacity flowrate determined from Equations 2.8 and 2.9. Now, we construct a TID in the usual manner. Table 2.9 shows a partial TID for Example 2.2.

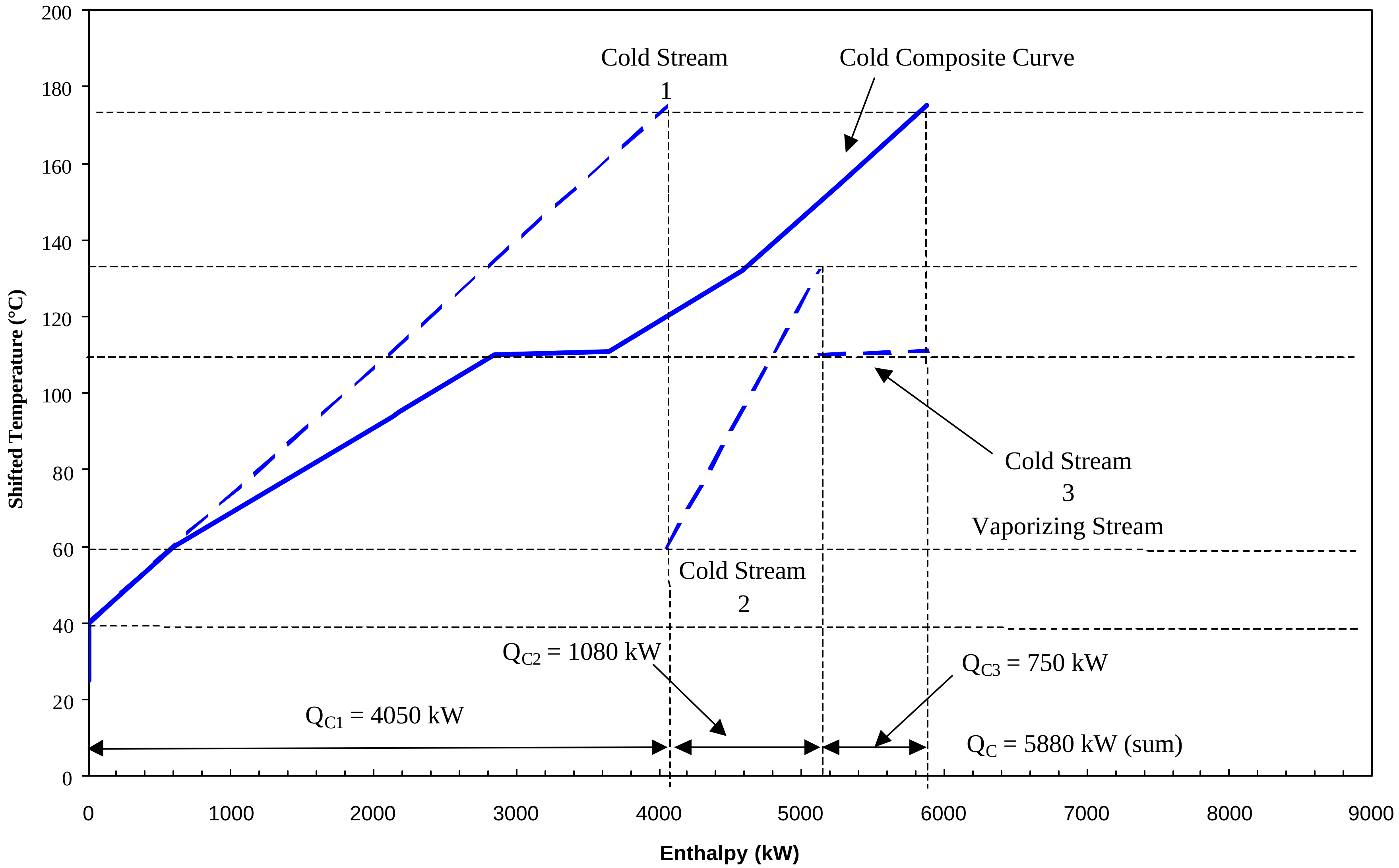

Figure 2.15. Graphical approach to constructing a cold stream composite curve for Example 2.2 with a vaporizing stream. Temperatures shifted for a minimum approach temperature.

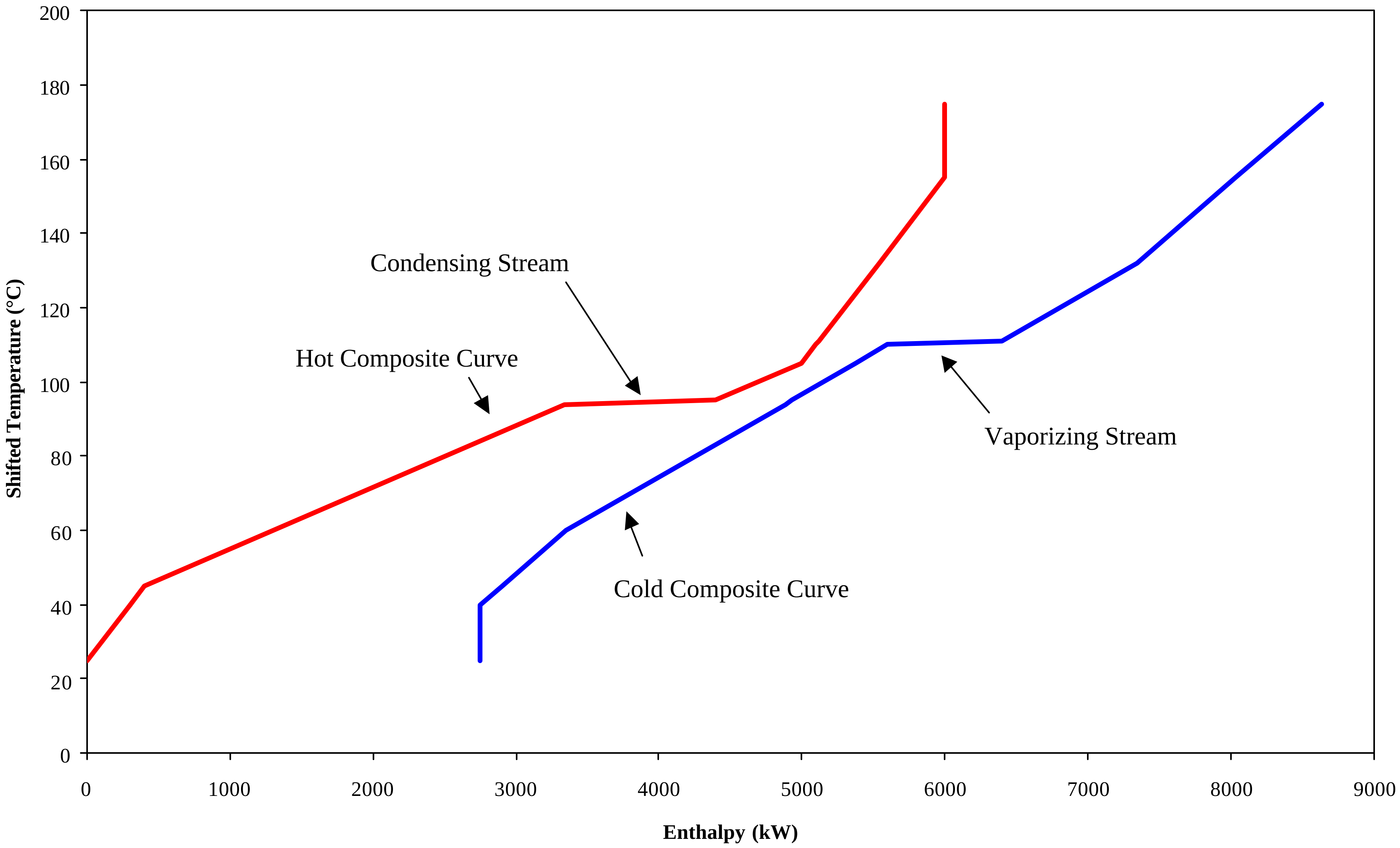

Figure 2.16. Hot and cold composite curves for Example 2.2 with condensing and vaporizing streams. Temperatures shifted for a minimum approach temperature.

Table 2.9. Partial TID for Example 2.2 with vaporizing and condensing streams.

	Hot Streams					Cold Streams				
Shifted Temperature (°C)	H1 20 kW/°C	H2 40 kW/°C	H2 10,000 kW/°C	Heat Surplus (kW)	Cumulative Surplus (kW)	C1 30 kW/°C	C2 15 kW/°C	C3 7,5000 kW/°C	Heat Deficit (kW)	Cumulative Deficit (kW)
25	▲				0					0
	│			300					0	
40	│				300	│				0
	│			100		│			150	
45	│	▲			400	│				150
	│	│		900		│			450	
60	│	│			1300	│	│			600
	│	│		2094		│	│		1570.5	
94	│	│	▲		3394	│	│			2170.5
	│	│	│	1006		│	│		4.5	
95	│	│	│		4400	│	│			2175
	│	│		600		│	│		450	
105	│	│			5000	│	│			2625
	│			100		│	│		225	
110	│				5100	│	│	│		2850
	│			20		│	│	│	795	
111	│				5120	│	│	▼		3645
	│			420		│	│		945	
132	│				5540	│	▼			4590
	│			460		│			690	
155	│				6000	│				5280
				0		│			600	
175					6000	▼				5880

2.5.3 Minimum Utility Targets

Once we have constructed either hot and cold composite curves or a TID for a given system, the final step is to determine the minimum utility targets using the concept of the pinch point. The concept of the pinch temperature is critical, as above that temperature, we do not use cooling utilities and below that temperature, we do not use heating utilities. Again, we can proceed either graphically or tabularly.

2.5.3.1 Graphical Approach: Hot and Cold Composite Curves

Once we have established hot and cold composite curves for the system, we can readily obtain the minimum utility targets simply by adjusting the cold composite curve to the left on the heat load axis until it just touches the hot composite curve at the pinch point:

1. Slide the cold composite curve to the left until it just touches the hot composite curve at the pinch temperature. Here, we refer to the pinch temperature with respect to a shifted temperature-interval boundary. Hot and cold streams are pinched at 10 °C above and below this temperature, respectively.

2. The horizontal distance at the bottom left represents the surplus heat of hot streams that is not removed by cold streams. This excess must be transferred to a cooling utility.

3. The horizontal distance at the top right represents the excess ability of the cold streams to remove heat from hot streams. Any excess must be heated with heating utilities.

Figure 2.17 illustrates the hot and cold composite curves for Example 2.1. In the figure, we identify the pinch at a shifted temperature of 105 °C. With a minimum approach temperature of 20 °C, hot streams are pinched at 115 °C while cold streams are pinched at 95 °C. We see a minimum cooling-utility duty (lower left) of 1375 kW and a minimum heating-utility duty (top right) equal to 1505 kW.

We return to Example 2.2 in Figure 2.18 and shift the hot and cold composite curves of Figure 2.16 to identify a pinch temperature of 105 °C and minimum heating and cooling duties of 2255 and 2375 kW, respectively.

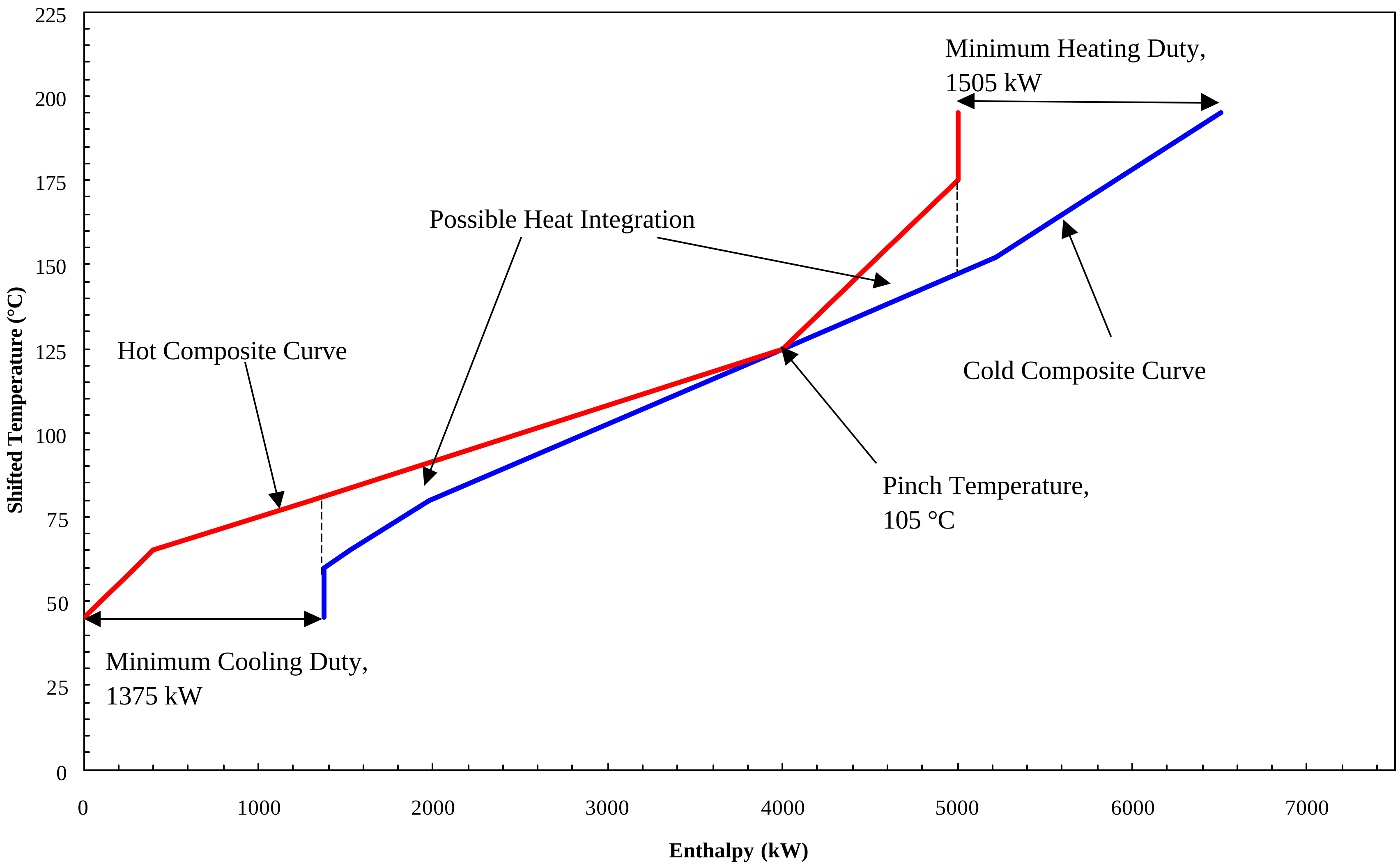

Figure 2.17. Hot and cold composite curves for Example 2.1 with minimum heating- and cooling-utility duties and the pinch temperature. Temperatures shifted for a minimum approach temperature of 20 °C.

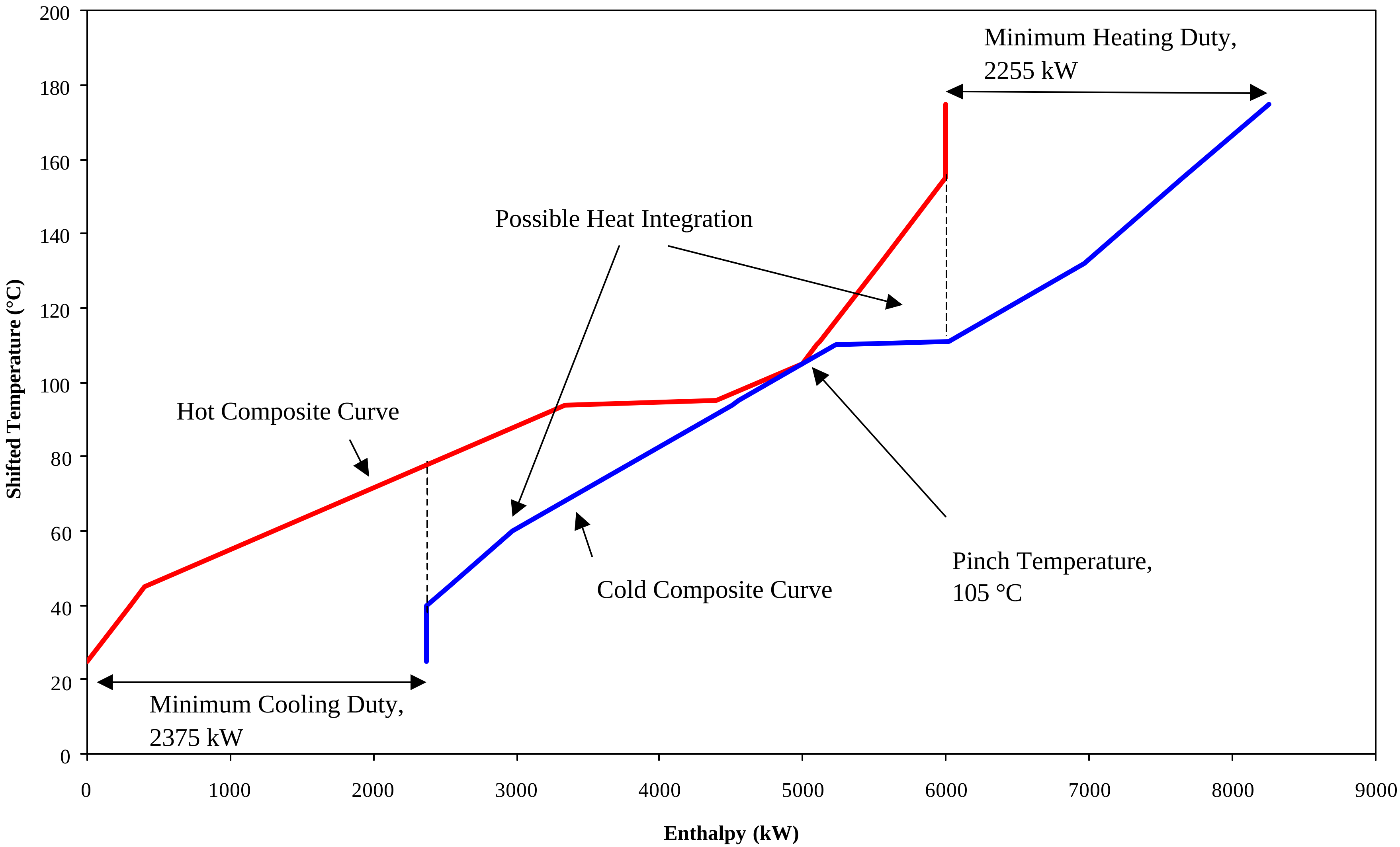

Figure 2.18. Hot and cold composite curves for Example 2.2 with the minimum heating- and cooling-utility duties. Temperatures shifted for a minimum approach temperature.

2.5.3.2 Tabular Approach: Temperature-Interval Diagram (TID)

Identifying the pinch temperature on a TID involves essentially the same principles as identifying the pinch temperature graphically. We add three columns to the TID of Table 2.9. The process is a very straightforward one, again more readily adaptable to computer programming than the graphical method:

1. In each temperature interval, evaluate the net heat surplus as the difference between the heat surplus from hot streams and the heat deficit of cold streams.

2. Cascade the net heat surplus starting with zero at the highest temperature-interval boundary (bottom). This reflects the flow of excess heat from higher temperature intervals to lower temperature intervals.

3. Place the negative of the minimum (most negative) value from the cascaded heat surplus column at the bottom temperature-interval boundary in the final column of the TID. Once again, cascade the net heat surplus starting with that value at the highest temperature-interval boundary (bottom right). The pinch temperature(s) are located where zeros are found in this column. The minimum cooling and heating duties are found at the top and bottom of the last column, respectively.

Table 2.10 shows the final CID, including the minimum utility targets, for Example 2.1. We identify the pinch at a shifted temperature (bold) of 105 °C by a zero in the last column.

Again, we see that the minimum cooling duty (italics) is 1375 kW (top right) and the minimum heating duty (italics) is 1505 kW (bottom right).

Table 2.11 shows the results for Example 2.2.

Table 2.10. Complete TID for Example 2.1.

	Hot Streams				Cold Streams						
Shifted Temperature (°C)	H1 20 kW/°C	H2 40 kW/°C	Heat Surplus (kW)	Cumulative Surplus (kW)	C1 30 kW/°C	C2 15 kW/°C	Heat Deficit (kW)	Cumulative Deficit (kW)	Net Heat Surplus (kW)	Cascaded Surplus (kW)	Adjusted Surplus (kW)
45	▲			0				0		-130	*1375*
	│		300				0		300		
60	│			300	│			0		-430	1075
	│		100		│		150		-50		
65	│	▲		400	│			150		-380	1125
	│	│	900		│		450		450		
80	│	│		1300	│	│		600		-830	675
	│	│	2700		│	│	2025		675		
125 (Pinch)	│	│		4000	│	│		2625		-1505	0
	│		540		│	│	1215		-675		
152	│			4540	│	▼		3840		-830	675
	│		460		│		690		-230		
175	│			5000	│			4530		-600	905
			0		│		600		-600		
195				5000	▼			5130		0	*1505*

Table 2.11. Complete TID for Example 2.2.

	Hot Streams					Cold Streams							
Shifted Temperature (°C)	**H1 20 kW/°C**	**H2 40 kW/°C**	**H2 10,000 kW/°C**	**Heat Surplus (kW)**	**Cumulative Surplus (kW)**	**C1 30 kW/°C**	**C2 15 kW/°C**	**C3 7,5000 kW/°C**	**Heat Deficit (kW)**	**Cumulative Deficit (kW)**	**Net Heat Surplus (kW)**	**Cascaded Surplus (kW)**	**Adjusted Surplus (kW)**
25	▲				0					0		170.0	*2375.0*
	│			300					0		300.0		
40	│				300	│				0		-130.0	2075.0
	│			100		│			150		-50.0		
45	│	▲			400	│				150		-130.0	2125.0
	│	│		900		│			450		450.0		
60	│	│			1300	│	│			600		-580.0	1675.0
	│	│		2094		│	│		1570.5		523.5		
94	│	│	▲		3394	│	│			2170.5		-1103.5	1151.5
	│	│	│	1006		│	│		4.5		1001.5		
95	│	│	│		4400	│	│			2175		-2105.0	150.0
	│	│		600		│	│		450		150.0		
105 (Pinch)	│	│			5000	│	│			2625		-2255.0	0
	│			100		│	│		225		-125.0		
110	│				5100	│	│	│		2850		-2130.0	125.0
	│			20		│	│	│	795		-775.5		
111	│				5120	│	│	▼		3645		-1355.0	900.0
	│			420		│	│		945		-547.5		
132	│				5540	│	▼			4590		-830.0	1425.0
	│			460		│			690		-230.0		
155	│				6000	│				5280		-600.0	1655.0
				0		│			600		-600.0		
175					6000	▼				5880		0	*2255.0*

2.6 Summary

- A heat-integration problem involves transferring heat from hot streams (decreasing their temperatures) to cold streams (increasing their temperatures) so that each stream reaches its desired target temperature while minimizing the utility consumptions (including heating and cooling utilities).

- Some common heating utilities include high-pressure steam, low-pressure steam and hot oil. Typical cooling utilities include cooling water and refrigerants.

- The maximum heating and cooling duties (without heat integration) are found when each cold stream is heated with a heating utility and each hot stream is cooled by a cooling utility.

- A minimum approach temperature for heat transfer, ΔT_{min}, is incorporated into the stream data by adding $\Delta T_{min}/2$ to the supply and target temperatures of each cold stream, and subtracting $\Delta T_{min}/2$ from the supply and target temperatures of each hot stream.

- We include condensing and vaporizing streams as hot and cold streams, respectively, with a 1 °C temperature change. We add 1 °C to condensing stream temperatures and subtract 1 °C from vaporizing stream temperatures.

- The temperature-enthalpy diagram is a useful tool for studying heat transfer within a heat exchanger.

- Minimum utility targets can be established for heating and cooling utilities through either a graphical technique, called the composite curve, or a tabular technique, termed the temperature-interval diagram (TID).

Nomenclature

ΔH_i	Total heat transferred from hot stream i or to cold stream i, kW
ΔT_{min}	Minimum approach temperature, °C
$\left(\dot{M}C_p\right)_i$	Capacity flowrate of process stream I, kW/ °C
$T^{supply}{}_i$	Supply temperature of process stream i, °C
$T^{target}{}_i$	Target temperature of process stream i, °C

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